IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant:	David Harbec *et al.*	Customer Number:	020988
Docket No.:	1770-322US	Confirmation No.:	2219
Serial No.:	10/535,050	Group Art:	1793
Filing Date:	January 30, 2006	Examiner:	Barcena, Carlos
Title:	METHOD FOR PRODUCING CARBON NANOTUBES USING A DC NON-TRANSFERRED THERMAL PLASMA TORCH		

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

DECLARATION OF DR. JEAN-LUC MEUNIER

UNDER 37 C.F.R.§ 1.132

Sir, I hereby declare and state:

1. I am a joint inventor of the subject matter presently claimed in the above-identified patent application.

2. I received a Bachelor's Degree in Engineering Physics in 1981 from École Polytechnique Fédérale De Lausanne, Switzerland, a Masters Degree in Énergie/Physiques des Plasmas from Institut National de la Recherche Scientifique, Canada in 1983 and a Doctorate in Énergie/Physiques des Plasmas from Institut National de la Recherche Scientifique, Canada in 1986. My CV is attached to this declaration in NSERC (Natural Sciences and Engineering Research Counsel of Canada) format. I have been conducting research in the field of thermal plasma and nanomaterials for over 28 years and have authored more than 150 scientific publications on the subject.

3. I have reviewed the Final Office Action mailed August 11, 2009, from the US Patent & Trademark Office in respect of the above noted application, including the positions taken by the PTO with respect to several prior art references. I have also particularly reviewed the subject

matter of Smiljanic et al. (Chem. Phys. Lett., 356, 2002, 189-193), Tsantrizos et al. (US Patent No. 5395,496), (hereinafter Tsantrizos #1), Matsumoto et al. (JP07061803), Tsantrizos et al. (US Patent No. 5,147,998) (hereinafter Tsantrizos #2), Cohen et al (US Patent No. 5,993,697) and Geobegan et al. (2002/0179564).

4. The present invention as claimed in the amended claims submitted simultaneously with this declaration is directed to a process for the manufacture of carbon nanostructures which may be carbon nanotubes or carbon nano-onions. The process involves the use of a high enthalpy metal electrode generated direct current thermal plasma torch which has a plasma forming gas feed and is connected to a cooled reactor. A metal catalyst is selected, which then determines the parameters of the process. Torch power may range from about 30kW up to a multi-megawatt level and the flow rate of the plasma gas feed and the reactor pressure are selected to provide a torch temperature required to vaporize and maintain the selected metal catalyst in the vapor state. A feed of a carbon containing substance and a carrier gas at a selected flow rate is provided to the cooled reactor in a quenching zone downstream of the plasma torch for the formation of carbon nanostructures. When the metal catalyst vapor is contacted by the carbon containing substance and carrier gas feed, *in situ* generation of metal catalyst nanoparticles having a diameter of from about 2 to about 30 nm occurs, along with the formation of atomic carbon. The metal nanoparticles act as a catalyst and nucleation points for the growth of carbon nanostructures of about the same diameter range. The carbon nanostructures are then collected from the reactor.

5. The selection of the metal catalyst will determine the operating parameters required for the process. Inherently, the feed of carbon containing substance and carrier gas which is fed to the cooled reactor downstream of the plasma torch into the quenching zone of carbon nanostructure formation is substantially cooler than the plasma torch flame. This allows formation of the required metal catalyst nanoparticles and the atomic carbon which form the carbon nanostructures. Keeping the catalyst vaporized until it is quenched to form the nanoparticles ultimately ensures the formation of the carbon nanostructures.

6. In one specific example of the present application, tungsten is selected as the catalyst metal. In my opinion, once the catalyst metal is selected, the operating parameters of the process can be determined and the plasma temperature achieved can be calculated using the parameters set for the process by the selection of the catalyst metal. An example of the calculations that one could make regarding the quench rate for the specific example in the

application is set out below. In my opinion these calculations are routine calculations that a person skilled in the relevant art could easily perform. Thus the use of the expressions "rapid quench" or "rapid cooling" have precise meaning in the context of the other parameters set out in the claims. All of this is to support the fact that the amended claims, which are all based on the description and hence are fully supported by the description, do define conditions that will provide the required rapid or fast quenching of the metal vapor that will produce the carbon nanostructures in accordance with the claimed process. The example of tungsten provided in the description together with the guidance found in the description and the claims will allow the person skilled in the art, once a catalyst metal has been selected, to determine the operating parameters that will ensure the production of carbon nanostructures every time using the claimed process.

7. Example of simplified calculations for the quench rate using data available in the patent example using He and using data given in Table I of the present application.

These calculations result in estimations of the average temperature of the plasma entering the plasma torch nozzle of around 13,000 °C, in estimations of the plasma flow velocity at the same position of around 8000 m/s (a supersonic velocity), and in estimations of the cooling rates of around 10^8 °C/s. Although the calculations are rough approximations of average values, these largely justify the terminology involving "high temperature", "high velocity" and "very high cooling rates".

Calculations:

Torch power: 30 – 65 kW; using **55 kW** in the present approximation, this being the power used in the demonstration experiment (US 2006/0127299A1 patent application, paragraph [0030]).

Main plasma gas flow rate: **225 slpm (paragraph [0035])**

Reactor pressure: 200, 500 Torr, and stated in patent to be between 200-800 Torr He (paragraph [0034]), we use here **760 Torr** (atmospheric pressure) to simplify calculations. This has little effect on the plasma temperature inside the torch (i.e. temperature entering the nozzle). The pressure in the reactor mainly modifies the plasma properties outside of the plasma torch.

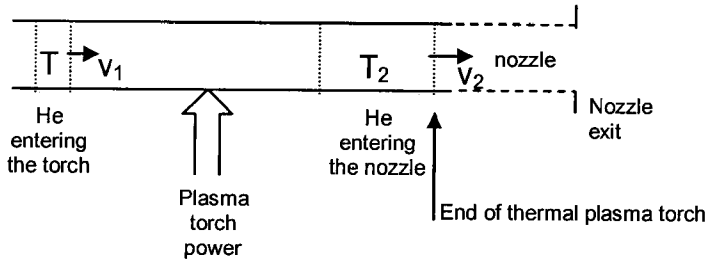
Mass flow rate of He:

225 slpm He = 225×10^{-3} m^3/min He(stp) = **3.75×10^{-3} m^3/s He** under standard conditions

of T and p (stp).

He density (standard conditions): ρ_{He} = **0.178 kg/m^3** [1]

Mass flow rate of He: $\dot{m} = (0.178\,\text{kg/m}^3)(3.67\cdot10^{-3}\ \text{m}^3/\text{s}) = \underline{6.53\cdot10^{-4}\ \text{kg/s}}$



Note that the carbon containing gas is injected only within the nozzle and is not present inside the plasma torch.

The change in heat energy content ($\dot{m}C_p\Delta T = \dot{m}C_p(T_2 - T_1) = W_p$) of the He gas entering at room temperature (**T_1=25°C = 298 K**) is, in a first approximation, the result of the energy input W_p from the plasma taking the torch efficiency into consideration:

Plasma torch power: 55 kW x 80% torch efficiency = 44 kW = 44 kJ/s = **44x10^3 J/s**

Specific heat C_p of the He gas [2]: ***C_p* = 5.193x10^3 J/kg K**. This value for He is a very weak function of temperature, it is for example 5.1931x10^3 J/kg K at 500 K, and still 5.1931x10^3 J/kg K at 6,200 K; 5.210x10^3 J/kg K at 9,000 K, and 5.267x10^3 J/kg K at 10,000 K. In this approximation, the constant value between room temperature and 7,500 K is used.

Estimated **average temperature of the plasma** entering the nozzle:

$$T_2 = T_1 + \frac{W_p}{\dot{m}C_p} = 298\,\text{K} + \frac{44\cdot10^3\ \text{J/s}}{(6.53\cdot10^{-4}\ \text{kg/s})(5.19\cdot10^3\ \text{J/kg}\cdot\text{K})} = 13008\,\text{K} \cong \underline{13000\,\text{K}}$$

Note: Accurate 2-D modeling of the flow and energy fields for the plasma gas entering the nozzle yield an average temperature of the flow around 16,000 K in the present condition of 55 kW and 225 slpm He [3].

Estimated flow velocities:

Using the perfect gas law linking the gas volume V with its temperature T: $pV=nRT$

Where R is the gas constant and n the number of moles (both R and n are constant here in our two volumes at T_1 and T_2), one can evaluate the volumetric expansion of

the gas as:

$$\frac{V_2}{V_1} = \frac{T_2}{T_1} = \frac{13000\ \text{K}}{298\ \text{K}} = 43.6$$

(If one uses instead T_2=6000 K as will occur further downstream of the plasma torch and nozzle, we get: V_2/V_1= **20.1**)

In the above calculations we considered the pressure relatively constant inside the torch. Since the pressure at the outlet is in fact slightly smaller than the inlet pressure, the expansion ratio and the outlet velocity will be further increased.

The cross section area of the plasma torch is constant throughout the calculation domain, the inside diameter of the plasma torch tubular electrode being 5 mm, a value typical for thermal plasma torches at this power level.

Neglecting the injection velocity, a minimum value of the flow velocity v_1 at the inlet can be evaluated using the volumetric flow rate of 225 slpm He = 3.75×10^{-3} m^3/s He:

$$v_1 = \frac{\dot{V}_1}{A_1} = \frac{3.75 \cdot 10^{-3}\ \text{m}^3/\text{s}}{\pi/4\,(5 \cdot 10^{-3}\ \text{m})^2} = 191\ \text{m/s}$$

Similarly, the outlet volumetric flow rate $\dot{V}_2$ being a factor 43.6 times higher than the inlet flow rate from thermal expansion, and the cross sectional area being constant, the **flow velocity of the plasma gas entering the nozzle** will be:

$$v_2 = 43.6(191\ \text{m/s}) = 8328 \cong \underline{8330\ \text{m/s}}$$

(If one uses T_2=6000 K downstream of the torch and nozzle, and assuming a relatively constant jet cross section, we get: **v_2=3840 m/s**)

Note: The more exact 2-D calculations in the model of Guo [3] leads to a velocity of roughly 5500 m/s, which is already supersonic.

Quench rate estimations:

The length of the nozzle is 3.7 cm = 3.7×10^{-2} m. We can estimate a minimum quench rate if one assumes this is the distance travelled by the plasma gas before being cooled to 3000 K or less (Reality: this distance is in fact shorter due (a) to the presence of supersonic shocks, (b) the cold gas (200 C, paragraph [0033]) injection in the nozzle, and (c) the diffusion to the cold (in reference to the plasma) tungsten walls maintained at ~1000 C). For tungsten used in the demonstration experiments, the temperature reached for forming carbon nanotubes is its eutectic temperature around 3000 K.

Time for the gas to travel 3.7 cm : $t = \frac{3.7 \cdot 10^{-2}\ \text{m}}{8330\ \text{m/s}} = 4.4 \cdot 10^{-6}\ \text{s}$

(If one uses T_2=6000 K we get: $t = 9.6 \cdot 10^{-6}\ \text{s}$)

Quench rate: $\frac{\Delta T}{t} = \frac{13000\ \text{K} - 3000\ \text{K}}{4.4 \cdot 10^{-6}\ \text{s}} = \underline{2.3 \cdot 10^{9}\ \text{K/s}}$

(If one usesT_2=6000 K we get: $\frac{\Delta T}{t} = 3.1 \cdot 10^{8}\ \text{K/s}$)

Note: The more exact 2-D modeling results of Guo [3] yields quench rates going above 5x10^7 K/s.

The value of 10^7 K/s used in the claim is conservative and strongly justifies the wording of "fast quench rates". Such value is many orders of magnitude above any quench rate values used in industrial reactors for chemical synthesis, and compares only with supersonic shock effects.

[1] CRC Handbook of Chemistry and Physics, 70th edition, p. B-19.
Or available on the web at http://en.wikipedia.org/wiki/Helium

[2] Table A.1, page 393 in: M.I. Boulos, P. Fauchais, E. Pfender, Thermal Plasmas Fundamentals and Applications, Vol. 1, Plenum Press, New York, 1994.

[3] L. Guo, Modeling of a supersonic DC plasma in CNT production, Ph.D. thesis, McGill University, 2009.

8. As the Examiner has recognized, Smiljanic *et al.* (Chemical Physics Letters 356, 189-193, 2002; hereinafter referred to as Smiljanic), does not explicitly teach using a high enthalpy plasma torch with a nozzle to produce the plasma used in carbon nanotube (CNT) production. Smiljanic discloses the fabrication of single wall carbon nanotubes using a **microwave plasma reactor,** a system operating in the non-thermal plasma regime meaning having different temperatures for electrons (light species) and atoms/molecules (heavy species), coupled to a furnace maintained at 1300° K, and having the carbon (ethylene) and catalyst (vaporized ferrocene) precursors injected in a vapor form into the microwave plasma. The calculations set out above clearly indicate that the process conditions now specified in the claims will produce temperatures that are not achievable in a microwave plasma torch. A microwave plasma torch using argon as in Smiljanic will generate atom/molecular temperatures (which correspond to the "gas" temperature of importance here for vaporization and reaction) having a maximum value around 2000 Kelvin (see Figures 2 and 4 of ref [4], and

Section 3 and Figure 6 in ref [5] giving $T_{g,max}$ of 1,400 K, the authors of these papers being the inventors and suppliers of the microwave torch used by Smiljanic), and it was shown that such maximum value cannot be increased by increasing the microwave power. It is to be noted that the temperature of 5,500 K indicated in the Smiljanic paper corresponds to a nitrogen plasma and not an argon plasma as used in their experiment. A nitrogen plasma is not favorable for carbon nanotube synthesis. In comparison, a DC thermal plasma torch using nitrogen reaches temperatures over 25,000 K (see page 370 of ref [2] in the calculations above, giving measured values up to this temperature). The temperature range between ~2,000 Kelvin and ~13,000 Kelvin calculated above for the DC thermal plasma experiment is not achieveable with the microwave reactor technology of Smiljanic. This means that both the chemistry involved at these high temperatures and the treatment of refractory materials (such as tungsten used in the present application) is not possible in Smiljanic. The supersonic flow and very high cooling rate attained in the present application are also not accessible by Smiljanic. The present application specifically uses supersonic flow, tungsten metal catalyst, and high temperature chemistry (atomic carbon generated from C_2Cl_4 molecule and reactions at temperatures above Cl-based side reactions) in the claimed process to generate the carbon nanotubes which are not found in Smiljanic.

[4] H. Nowakowska, Z. Zakrzewski, M. Moisan, and M. Lubanski, Propagation characteristics of surface waves sustaining atmospheric pressure discharges: the influence of the discharge processes, J. Phys. D: Appl. Phys. 31, 1422-1432, 1998.

[5] M.D. Calzada, M. Moisan, A. Gamero, A. Sola, Experimental investigation and characterization of the departure from local thermodynamic equilibrium along a surface-wave-sustained discharge at atmospheric pressure, J. Appl. Phys., 80, 1, 1996.

9. In Tsantrizos *et al* (USPN 5,395,496, hereafter Tsantrizos #1), there is disclosed the use of a DC thermal plasma torch for the **homogeneous chemical reaction process** to form fullerene molecules (C_{60} and C_{70}) in a plasma environment specifically attempting to maintain a large and uniform temperature environment. Thus a combination of Tsantrizos #1 and Smiljanic does not provide the presently claimed process, since the vaporization of the catalyst metal to provide metal catalyst nanoparticles which act as nucleation points and catalyst for the growth of carbon nanostructures is not arrived at. There is no teaching of the handling of a metal vapor carrying thermal plasma jet for a heterogeneous reaction process based on the nanoparticles nucleated from the metal vapors.

10. In Matsumoto *et al.* (JP 07061803), there is disclosed the use of an inductively coupled plasma using carbon powders only, with **no use of catalyst** being specified, to form a very

low yield (5-10%) of a **mixture** of fullerenes and carbon nanotubes. Matsumoto does not teach a heterogeneous reaction involving the handling of metal vapors for the formation of nanoparticles of catalyst. This reference does not motivate the combination of Smiljanic and Tsantrizos #1 for these reasons.

11. In my opinion therefore, it is clear that combining Smiljanic and Tsantrizos #1, with the teachings of Matsumoto in mind, does not lead to the presently claimed process which involves rapid quench rates and conditions leading to supersonic flows, such as jet expansion in the nozzle, pressures below atmospheric, and very high plasma flow rates, which are not taught or suggested in the combination of the three references.

12. In Geobegan *et al* (US2002/0179564A1; thereafter called Geobegan), a method is established for the generation of carbon nanorods and carbon nanotube structures in a **two-step process** termed "***condensed phase conversion growth***" (paragraph [0057] and claims 4, 8, 9 in Geobegan) in which a first step is providing a "*condensed phase*" matrix material deposited on a surface (Claims, 4, 9 in Geobegan), which condensed phase does not contain the carbon nanotube material but rather contains mixtures of carbon powder and catalyst powder in an aggregated state (Figure 1 in Geobegan). This is followed by a second post-treatment step called the "*conversion growth*" of the nanotube structure by a treatment of the "***solid or powdered material instead of vapor***" (paragraph [0056] in Geobegan), which solid/powder material was deposited in the first step. In their proof of principle experiments, the deposit formed in the first step is later heated in vacuum or in a gas to initiate the growth of carbon nanotubes. Various strategies, including DC thermal plasma torch, are used to produce the initial condensed phase acting as a source material (paragraph [0059] in Geobegan). These strategies highlight the importance of supplying the particles to a substrate at a high rate in a particle conversion epitaxy process (paragraph [0062] in Geobegan), i.e for the formation of the solid precursor deposit. The method in Geobegan describes a transformation to the carbon nano-structures after the deposition of a solid precursor in a post-processing step in a way similar to the chemical vapor deposition (CVD) processes for the growth of carbon nanotubes on surfaces and structural components (paragraph [0090] in Geobegan). **Geobegan does not teach a method to generate carbon nanotubes in the gas phase. Geobegan also does not teach a control of the gas dynamics that would make possible the formation of carbon nanotubes in flight within a thermal plasma jet making a continuous one-step formation process possible as in the present application. Geobegan teaches a method to generate a solid precursor material**

that makes possible the CVD-like carbon nanotube process to be made in a post-processing step.

13. I am also of the opinion that back in 2002, it was not known by those skilled in the art or from the literature that there could be advantages to the use of rapid quench rates for example from a supersonic flow, as both systems of Smiljanic and Tsantrizos teach a requirement of relatively uniform conditions; Smiljanic uses an oven at the outlet of his microwave plasma to maintain longer residence times at a uniform temperature, while Tsantrizos sets a spherical geometry of the reactor in order to generate more uniform temperature profiles. Even at the present time, other researchers and experts in the field of thermal plasmas are indicating their unsuccessful attempts to produce CNTs using the DC thermal plasma torch technology (this was officially indicated at the 2007 Round Table on Thermal Plasma Technology, Sharm El Sheik, Egypt; it also follows from the absence of thermal plasma torch papers on this topic (apart from those of Harbec and Meunier) in the International Symposium on Plasma Chemistry (most important international conference for thermal plasma technology) up to year 2007).

14. Copies of all references referred to herein are attached to this Declaration.

15. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further, that these statements were made with the knowledge that willful false statements and the like, so made, are punishable by fine or imprisonment, or both, under 18 U.S.C. §1001 and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

Respectfully submitted,

November 7, 2009
Date

Dr. Jean-Luc Meunier

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

FORM 100
Personal Data Form
PART I

Date: 2009/10/28

Family name	Given name	Initial(s) of all given names	Personal identification no. (PIN)
Meunier	Jean-Luc	J.L.	17858

☐ I hold a faculty position at an eligible Canadian college (complete Appendices B1 and C)

☐ I do not or will not hold an academic appointment at a Canadian postsecondary institution

Place of employment other than a Canadian postsecondary Institution (give address in Appendix A)

APPOINTMENT AT A POSTSECONDARY INSTITUTION

Title of position: Associate Professor

Department: Chemical Engineering

Campus: McGill

Canadian postsecondary institution: McGill

Tenured or tenure-track academic appointment: Yes [X] No [ ]

Part-time appointment [ ] Full-time appointment [X]

- For all non-tenured or non tenure-track academic appointment and Emeritus Professors, complete Appendices B & C
- For life-time Emeritus Professor and part-time positions, complete Appendix C

ACADEMIC BACKGROUND

Degree	Name of discipline	Institution	Country	Date yyyy/mm
Bachelor's	Engineering Physics	École Polytechnique Fédérale de Lausanne	SWITZERLAND	1981/01
Master's	Énergie / Physique des plasmas	Institut national de recherche scientifique-Énergie	CANADA	1983/04
Doctorate	Énergie / Physique des plasmas	Institut national de recherche scientifique-Énergie	CANADA	1986/07

TRAINING OF HIGHLY QUALIFIED PERSONNEL

Indicate the number of students, fellows and other research personnel that you:

	Currently		Over the past six years (excluding the current year)		
	Supervised	Co-supervised	Supervised	Co-supervised	Total
Undergraduate	5	1	10		16
Master's	1		5	6	12
Doctoral	1	3	2		6
Postdoctoral	1		3		4
Others			1		1
Total	8	4	21	6	39

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Personal identification no. (PIN)	Family name
17858	Meunier

ACADEMIC, RESEARCH AND INDUSTRIAL EXPERIENCE (use one additional page if necessary)

Position held (begin with current)	Organization	Department	Period (yyyy/mm to yyyy/mm)
Associate Professor	McGill	Chemical Engineering	1996/06
Assistant Professor	McGill University	Chemical Engineering	1990/06 to 1996/05
Research Associate	McGill University	Chemical Engineering	1986/08 to 1990/05
Research Engineer	Hydro-Quebec	Institut de recherche H.-Q. (IREQ)	1984/08 to 1986/08
Research Assistant	École Polytechnique Fédérale de Lausanne	C. Recher en physique des plasmas (CRPP)	1980/07 to 1981/06
Research Assistant	École Polytechnique Fédérale de Lausanne	IMAC, Génie Civil	1978/06 to 1978/09

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17858	Meunier

RESEARCH SUPPORT

List all sources of support **(including NSERC grants and university start-up funds)** held as an applicant or a co-applicant: a) support held in the past four (4) years but now completed; b) support currently held, and c) support applied for. For group grants, indicate the percentage of the funding directly applicable to your research. Use additional pages as required.

Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)
a) Support held in the past 4 years			
Terreault B., 23 univ. professors, 16 ind. res.	Plasma Québec - Réseau thématique en sciences et applications avancées des plasmas FCAR Regroupements stratégiques 5 hours/month	440,000 (5%) 440,000 (5%) 440,000 (5%) 440,000 (5%)	2002 2003 2004 2005
Meunier, J-L (P.I.), Coulombe, Munz, Gauvin, Drew	Development of new advanced electrode materials for electric arc devices CRSNG Strategic projects 15 hours/month	202,720 (35%) 173,720 (35%) 173,720 (35%)	2003 2004 2005
Coulombe, S (P.I.), Meunier JL, Gauvin R	Développement d'un procédé plasma pour la synthèse des nanofluides FQRNT Équipe 10 hours/month	51,250 (20%) 51,250 (20%) 43,750 (10%)	2006 2007 2008
Margot, J. (PI) + 39 researchers from 4 Universiti	Plasma-Québec: Un regroupement stratégique en sciences et applications des plasmas FQRNT Centre 10 hours/month	140,000 (3%) 140,000 (3%)	2006 2007

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Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)
a) Support held in the past 4 years			
Meunier, J.-L.	Modélisation numérique d'une torche à plasma DC à air soufflé dans un réacteur de gazéfication FQRNT/MITACS Programme de stage post-doctoral 10 hours/month	15,000	2008
Meunier, J.-L.	Modélisation numérique d'une torche à plasma DC à air soufflé dans un réacteur de gazéfication PyroGenesis Inc. Programme de stage post-doctoral FQRNT/MITACS (contr. ind.) 10 hours/month	15,000	2008
b) Support currently held			
Meunier, Jean-Luc	Plasma-surface interactions for nano-comp. materials and arc-electrode phen. NSERC Discovery Grant 35 hours/month	32,500 32,500 32,500 32,500 32,500	2005 2006 2007 2008 2009
Stansfield, B(P.I.), Dodelet,Berk,Meunier	The synthesis and functionalization of nanostructured carbon black by plasma for use in fuel cells NSERC Strategic 10 hours/month	146,200 (35%) 136,200 (35%) 144,700 (35%)	2006 2007 2008

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RESEARCH SUPPORT

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Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)
b) Support currently held			
Chaker M. (PI) & Plasma-Québec researchers	Laboratoire en sciences et applications des plasmas Fondation canadienne pour l'innovation Fonds d'opération des infrastructures (McGill share only)	27,551 (33%) 32,995 (33%) 32,995 (33%) 32,995 (33%) 32,995 (33%)	2007 2008 2009 2010 2011
Meunier J.-L., Coulombe S., Munz R.J.	Plasma-Québec/McGill McGill University VP(Research) Centers	14,037 (33%) 14,037 (33%)	2008 2009
Margot J, and Plasma-Qu/bec members	Regroupement Plasma-Québec FQRNT Regroupements stratégiques	330,000 (5%) 330,000 (5%) 330,000 (5%) 330,000 (5%) 330,000 (5%)	2008 2009 2010 2011 2012
Meunier J.-L.	Modélisation numérique de torches à plasma DC à air soufflé - 2e partie FQRNT/NSERC/Mitacs Programme de stage post-doctoral 10 hours/month	20,000	2009

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RESEARCH SUPPORT

List all sources of support **(including NSERC grants and university start-up funds)** held as an applicant or a co-applicant: a) support held in the past four (4) years but now completed; b) support currently held, and c) support applied for. For group grants, indicate the percentage of the funding directly applicable to your research. Use additional pages as required.

Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)
b) Support currently held			
Meunier J.-L.	Modélisation numérique de torches à plasma DC à air soufflé - 2e partie PyroGenesis Inc. Programme de stage post-doctoral (contr. ind.) 10 hours/month	10,000	2009
c) Support applied for			
Coulombe, Sylvain (PI); Meunier JL	Mercury-free discharge lamp based on CNT array electrodes NSERC Idea to Innovation, Phase 1 10 hours/month	108,750 (50%)	2010
Coulombe, Sylvain (PI) + 8 researchers	Tabletop scanning electron microscope NSERC Research Tools and Infrastructure	118,576 (12%)	2010
Omanovic, Sasha	Imaging Ellipsometry System for Advanced Materials Characterization NSERC Research Tools and Instrumentation - Category 1	129,554 (5%)	2010

Highly Qualified Personnel (HQP)

Provide personal data about the HQP that you currently, or over the past six years, have supervised or co-supervised.

Personal identification no. (PIN)	Family name
17858	Meunier

Name	Type of HQP Training and Status	Years Supervised or Co-supervised	Title of Project or Thesis	Present Position
Vandsburger, Leron	Doctoral (In Progress)	Co-supervised 2009 -	Study of carbon nanotubes based electrodes for fluorescent..	Ph.D. student, McGill University
Mendoza Gonzalez,	Postdoctoral (In Progress)	Supervised 2008 -	Numerical Modeling of a DC Thermal Plasma Torch	PDF, Chemical Engineering, McGill University
Pristavita-Tur(Ramona	Doctoral (In Progress)	Co-supervised 2007 -	Functionalized carbon production for PEM fuel cells	Ph.D. student, McGill University
Baddour, Carole	Doctoral (In Progress)	Supervised 2005 -	CNT/TiN nano-composite films on stainless steel	Ph.D. student, McGill University
Dionne, Martin	Doctoral (In Progress)	Co-supervised 2005 -	Modeling and exp. study of plasma/CNT surface interaction	Ph.D. student, McGill University
Larissa, Jorge	Undergraduate (Completed)	Co-supervised 2009 - 2009	Polymer-CNT composites using plasma functionalization	UG student, McGill University
Morier, Geoffrey	Undergraduate (Completed)	Supervised 2009 - 2009	DLC films using an arc-PVD source	UG student, McGill University
Pascone, Pierre-Alexan(	Undergraduate (Completed)	Supervised 2009 - 2009	Electrochemical surface area measurements of CNT covered ele	UG student, McGill University
Pasieka, James J.	Undergraduate (Completed)	Supervised 2009 - 2009	CNT ablation study using a CO2 laser	UG student, McGill University
Upham, David	Undergraduate (Completed)	Supervised 2009 - 2009	Th-CVD of CNT in a fluidized bed (Part 2)	UG student, McGill University
Valla, Sebastien	Undergraduate (Completed)	Supervised 2009 - 2009	CFD modeling of the flow/temperature fields in CVD	UG student, McGill University
Vandsburger, Leron	Master (Thesis) (Completed)	Co-supervised 2007 - 2009	Synthesis & covalent surface modification of carbon nano...	Ph.D. student. McGill University
Guo, Liping	Postdoctoral (Completed)	Supervised 2008 - 2008	Modeling of a DC thermal plasma torch	Shaw Energy & Chemical Group, USA
Jaung, Sarah	Undergraduate (Completed)	Supervised 2008 - 2008	Characterization of SS substrate surface prior to CNT growth	UG student, McGill University
Moran, Blain	Undergraduate (Completed)	Supervised 2008 - 2008	Study of PAH content in carbon black in the context of fuel	UG student, McGill University
Upham, David	Undergraduate (Completed)	Supervised 2008 - 2008	Th-CVD of CNT on SS powders (part 1)	UG student, McGill University
Azem, Amir	Master(Thesis) (Completed)	Supervised 2005 - 2008	Growth of nitrogen doped diamond films using ICP...	(Germany)
Guo, Liping	Doctoral (Completed)	Supervised 2002 - 2008	Modeling of a supersonic DC plasma torch in CNT production	Shaw Energy & Chemical Group, USA
Mitra, Reema	Undergraduate (Completed)	Supervised 2007 - 2007	Th-CVD growth of CNT on SS: surface morphology opt.	(unknown - recently graduated)
Nasuroglu, Deniz	Master(Thesis) (Completed)	Co-supervised 2006 - 2007	Synthesis of CNT ... applications in electreoch. capacitors	Ph.D. student, McGill University

Highly Qualified Personnel (HQP)

Provide personal data about the HQP that you currently, or over the past six years, have supervised or co-supervised.

Personal identification no. (PIN)	Family name
17858	Meunier

Name	Type of HQP Training and Status	Years Supervised or Co-supervised	Title of Project or Thesis	Present Position
Dai, Gui-Ping	Postdoctoral (Completed)	Supervised 2005 - 2007	CNT synthesis using a thermal plasma process	Research Associate, USA
Fadlallah, Faysal	Master(Thesis) (Completed)	Supervised 2005 - 2007	Prep. of metal-CNT composite powders for th. plasma spraying	Future Pipe Industries, Dubai
Reddy, Naveen K.	Master(Thesis) (Completed)	Co-supervised 2005 - 2006	CVD growth of oriented carbon nanotubes for electrode applic	Ph.D. student, Belgium
ElMallah, Nadine	Master(Thesis) (Completed)	Supervised 2004 - 2006	CNT transport in a PVD reactor for arc electrode application	Industry, Canada
Hinkov, Ivaylo	Postdoctoral (Completed)	Supervised 2004 - 2006	CNT synthesis using inductively coupled plasma with C2Cl4 pc	Researcher, France
Roy, François	Master(Thesis) (Completed)	Co-supervised 2004 - 2006	Nanoscale island of dielectric material on Cu by ion implant	Ph.D., EPFL, Switzerland
Harbec, David	Doctoral (Completed)	Supervised 2002 - 2006	Carbon nanotube catalytic synthesis using dc plasma torch	Post-doc, Université de Sherbrooke
Beaulieu-Berg S.	Undergraduate (Completed)	Supervised 2004 - 2004	Plasma spraying of Cu-CNT nanocomposite	PhD Student, McGill University
(Name withheld)	Undergraduate (Completed)	Supervised 2004 - 2004	Modeling of the temperature profile in graphite arc electrod	(unknown)
(Name withheld)	Undergraduate (Completed)	Supervised 2004 - 2004	Modeling heat transfer in graphite arc electrode for CNT syn	(unknown)
(Name withheld)	Undergraduate (Completed)	Supervised 2004 - 2004	CNT synthesis from arc-based device in liquid precursor	(unknown)
(Name withheld)	Master(non-th.) (Completed)	Supervised 2004 - 2004	Study of fullerene content from CNT reactor based on C2Cl4	unknown
Tariq, Amna	Master(Thesis) (Completed)	Co-supervised 2002 - 2004	Nanocomposite formation based oin C60 imbedded in polymer fi	Industry
Jureidini, Joelle	Undergraduate (Completed)	Supervised 2003 - 2003	TGA calibration for CNT characterization from synth.	(unknown)
Lamontagne, Mélanie	Undergraduate (Completed)	Supervised 2003 - 2003	Raman spectroscopy on CNT containing soot	(unknown)

Part II. Research Contributions (updated October 24 2009)

1. Most Significant Contributions to Research and Applications

1.1 Arc/cathode surface interaction: Erosion and AIP contributions

Success in modeling the local plasma-cathode phenomena led to important scientific advances in the understanding of this interaction, with theoretical and experimental expertise developed over the last 20 years and leading to three (3) patents (2 of these applied in 2009) and 8 journal papers in the last 6 years; we are forming one of the leading team in the world in this area. A global approach to solve problems of electrode degradation using nano-composite materials is presently leading to a new family of electrode systems based on carbon nanotubes; the two patent applications made in 2009 are based on (1) a new low voltage high current flux cathode source from a "properly" designed nanotube array, and (2) from an innovative open nanocomposite "felt" structure yielding 3D volumetric emission from the surface.

1.2 Carbon nanotubes synthesis and applications

We first developed a process for the production of carbon nanotubes (CNT) and fullerenes using a supersonic thermal plasma technology (Patent WO-A1 2004046030) and a liquid or gas carbon precursor. The process is developed using a 100kW DC plasma torch, and has an important scale-up potential for industrial production of this advanced material (on this topic in the last 6 years: 4 graduate student projects, 2 USRA, 2 journal papers, 10 conference papers). We also developed recently the technology to grow carbon nanotubes directly on stainless steel metal surfaces without the need of an external catalyst, a technique that is now opening a wide range of applications and showing an important impact on the research community, as reflected by the 6 graduate students and 8 USRA projects on this topic in the last 6 years (+2 journal & 9 conf. papers). Both techniques discussed above generated papers in the journal Carbon, a highly rated international journal (impact factor: 4.37). Another technique developed recently relates to an "easy" template formation and nanotube growth process on aluminum oxide (see the first 2009 patent), this technique providing the surface morphology for electrode with strongly enhanced electron emission (3 journal & 9 conf. papers, including the best paper award at ISPC-19(2009) in Germany [99]). The CNT work was generic and now applies to novel devices (new plasma source by M. Dionne, Ph.D) and original concepts (3-D open volumes on surfaces, C. Baddour, Ph.D). Other applications in the fields of energy and materials are now studied. In parallel to CNT work and using the expertise generated in this field, new carbon based materials (carbon nano-flakes) are now being developed for advanced catalyst structures and platinum replacement in fuel cells.

1.3 Diamond films and RF thermal plasma CVD

Research on diamond film growth using bias assisted thermal plasmas provided local values in the diamond growth process. This was a very challenging task as the substrates are immersed in thermal plasma flames (~5000K) with RF floating potentials (~1 kV) oscillating at 4 MHz. Such local values gave *in situ* real time indications on the film nucleation and growth processes to a point where new monitoring and control parameters have been defined. These results led to the growth of nitrogen doped diamond films for potential applications in electrochemical devices (ex.: for water treatment).

2. Research Contributions (Bold: graduate/UG students supervised)

2.1 Refereed journal publications: (2003-present)

51. **M. Dionne**, S. Coulombe, J.-L. Meunier, *Energy exchange during electron emission from carbon nanotubes: Considerations on tip cooling effect and destruction of the emitter*, Phys. Rev. B, 80, 085429, 2009.
50. **L. Vandsburger**, E.J. Swanson, J. Tavares, J.-L. Meunier, S. Coulombe, *Stabilized aqueous dispersion of multi-walled carbon nanotubes obtained by RF glow discharge treatment*, J. Nanoparticle Research, 11, 7, 1817-22 (DOI 10.1007/s11051-009-9656-4) 2009.
49. **C.E. Baddour, F. Fadlallah, D. Nasuhoglu, R. Mitra, L. Vandsburger**, J.-L. Meunier, *A simple thermal CVD method for carbon nanotube synthesis on stainless steel 304 without the addition of an external catalyst,* CARBON, Vol. 47, 1, pp. 313-318, (doi:10.1016/j.carbon.2008.10.038) 2009 .
48. J. Tavares, S. Coulombe, J.-L. Meunier, *Synthesis of cubic-structured monocrystalline titanium nitride nanoparticles by means of a dual plasma process*, J. Phys. D: Appl. Phys, 42, 10, 1-4, 2009.
47. M. Kandah, J.-L. Meunier, *Production of Carbon Nanotubes-Nickel Composites on Different Graphite Substrates*, Fluid Dynamics and Materials Processing, Vol. 5, No. 2, 123-136, 2009.
46. **M. Dionne**, S. Coulombe, J.-L. Meunier, *Field emission calculations revisited with Murphy & Good theory:a new interpretation ofthe Fowler-Nordheim plot*, J. Phys. D: Appl. Phys.,41,24,1-8, 2008.
45. M. Kandah, J.-L. Meunier, *Production of carbon nanotubes on different monel substrates*, Fluid Dynamics & Materials Processing, Vol. 4, No. 4, pp. 231-236, 2008.
44. **M. Dionne**, S. Coulombe, J.-L. Meunier, *Screening effects between field-enhancing patterned carbon nanotubes : A numerical study*, IEEE Trans. Electron Dev., Vol. 55, 6, 1298-1305, 2008.
43. L. Rao, R.J. Munz, J.-L. Meunier, *Vacuum arc velocity and erosion rate measurements on nanostructured plasma and HVOF coatings*, J. Phys. D: Appl. Phys. 40, 4192-4201, 2007.
42. **D. Harbec**, J.-L. Meunier, **L. Guo, J. Jureidini**, *A parametric study of carbon nanotubes production from tetrachloroethylene using a supersonic thermal plasma jet*, Carbon, 45, 2054-2064, 2007.
41. **F. Roy**, G. Abel, B. Terreault , A. Reguer, J.-L. Meunier, M. Bolduc and G.G. Ross, *On-line system for temperature and accumulated dose control in Plasma-Based Ion Implantation*, Rev. Sci. Instrum., 78, 023905, (doi: 10.1063/1.2472601) 2007.
40. J.-L. Meunier, S. Coulombe, M. Kandah, Erosion of carbon arc cathodes operating in the thermo-field electron emission mode, Plasma Sources Sci. & Technol., 16, 33-41, 2007.
39. M. Kandah, J.-L. Meunier, Removal of Nickel Ions from Water by Multi-Walled Carbon Nanotubes, J. Hazardous Materials, 146, 1-2, 283-288, July 2007.
38. L. Rao, **N.K. Reddy**, S. Coulombe, J.-L. Meunier, R. J. Munz, *Carbon Nanotubes as Nanoparticles Collector,* Journal of Nanoparticle Research, 9, 4 689-695, 2007.
37. L. Rao, R.J. Munz, J.-L. Meunier, *Vacuum arc velocity and erosion rate measurements on nanostructured plasma and HVOF spray coatings,* J. Phys. D: Appl. Phys. 41, 19,4192-4201, 2008.
36. **N.K. Reddy**, J.-L. Meunier, S. Coulombe, *Growth of carbon nanotubes directly on a nickel surface by thermal CVD*, Materials Letters, 60, 3761-3765, 2006.
35. J.-L. Meunier, **M. Kandah, M. Campbell**, *Columnar diamond film coverage of vacuum arc erosion canyons on graphite,* IEEE Trans. Plasma Sci., 33, 2, 238-239, April 2005.
34. E.. Amorim, L. Levy, D. Sarrail, J.-P. Gardou , J.-L. Meunier, K. Bogus, S. Vacquié, , *Secondary discharges on solar arrays: vacuum arcs across adjacent biased cells*, J. of Spacecraft and Rockets, 42, 2, 329-335, March-April 2005.
33. **D. Harbec**, J.-L. Meunier, **L. Guo**, R. Gauvin, **N. El Mallah**, *Carbon nanotubes from the dissociation of C2Cl4 using a dc thermal plasma torch*, J. Phys. D: Appl. Phys., 37, 2121-26, 2004.
32. K. Saidane, M. Razafinimanana, H. Lange, A. Huczko, M. Baltas, A. Gleizes, J.-L. Meunier, *Fullerene synthesis in the graphite electrode arc process : local plasma characteristics and correlation with yield*, J. Phys.D: Appl. Phys., 37, 232-239, 2004.
31. **J. Oberste-Berghaus**, J.-L. Meunier, F. Gitzhofer, *Monitoring and control of RF thermal plasma diamond deposition via substrate biasing*, Meas. Sci. Technol., 15, 161-164, 2004.

30. J.-L. Meunier, **M. Campbell**, M. Kandah, *Evidence of columnar diamond growth structures within cathode spot craters of vacuum arcs on carbon*, J. Phys. D: Appl. Phys., 36, 3138-3143, 2003
29. **J. Oberste Berghaus**, J.-L. Meunier, F. Gitzhofer, *Direct current bias effects in RF induction thermal plasma diamond CVD,* IEEE Trans. Plasma Science, Vol. 30, No. 1, pp. 442-449, Feb 2002.
28. **S. Coulombe** and J.-L. Meunier, *Theoretical prediction of non-thermionic arc cathode erosion rate including both vaporization and melting of the surface*, Plasma Sources Sci. & Technol., 9, 3, pp.239-247, Aug. 2000.
27. J.-L. Meunier, *Cathodic Arc Carbon Plasma / Gas Interaction in Fullerenes Synthesis Study*, J. Appl. Phys., 85, 3, pp. 1992-1994, 1999.
26. J.-L. Meunier, **S. Coulombe**, *Cold Cathode Arc Attachment: The Importance of the High Local Pressure*, Pure & Applied Chemistry, 70(6), 1175-1180, June 1998.
25. **J. Oberste-Berghaus**, J.-L. Meunier and F. Gitzhofer, *Diamond Coatings for Tool Shafts by Induction Plasma Deposition*, Int. J. of Refractory Metals and Hard Material,s, Vol 16, No. 3, pp. 197-201, 1998.
24. **S. Coulombe**, J.-L. Meunier, *Comparison of electron emission equations used in arc-cathode interaction calculations*, J. Physics D: Applied Phys., Vol. 30, No. 20, pp. 2905-2910, Oct. 1997.
23. **J.-F. Bilodeau**, **Th. Alexakis**, J.-L. Meunier, P.G. Tsantrizos, *Model of the synthesis of fullerenes by the plasma torch dissociation of C_2Cl_4*, J. Phys. D: Appl. Phys, 30, pp. 2403-2410, 1997.
22. **J. Oberste-Berghaus**, J.-L. Meunier, F. Gitzhofer, *Local growth studies of CVD diamond using a probe-like substrate*, IEEE Trans. Plasma Sci., Vol. 25, No. 5, p. 1058, Oct. 1997.
21. **Th. Alexakis**, J.-L. Meunier, Y.S. Tsantrizos, P.G. Tsantrizos, *Synthesis of fullerenes via the thermal plasma dissociation of hydrocarbons*, Appl. Phys. Lett., 70 (16), pp. 2102-2104, Apr.1997.
20. **S. Coulombe**, J.-L. Meunier, *Arc-cold cathode interactions: parametric dependence on local pressure*, Plasma Sources Science & Tech., Vol. 6, No. 4, pp. 508-517, 1997.
19. **S. Coulombe**, J.-L. Meunier, *Importance of high local cathode spot pressure on heat transfer to thermal arc cold cathode*, IEEE Trans. Plasma Sci., Vol. 25, No. 5, p. 913-918, Oct. 1997.
18. **S. Coulombe**, J.-L. Meunier, *Thermo-field emission: A comparative study*, J. Phys. D: Appl. Phys., 30, 5, pp. 776-780, March 1997.
17. **M. Kandah**, J.-L. Meunier, *Erosion study on graphite cathodes using pulsed vacuum arcs*, IEEE Trans. Plasma Sci., Vol. 24, No. 2, pp. 523-527, Apr. 1996.
16. **M. Kandah,** J.-L. Meunier, *Vacuum arc cathode spot movement on various kinds of graphite cathodes*, Pl. Sources Sci & Tech., 5, pp. 349-355, 1996.
15. **N. Desaulniers-Soucy**, J.-L. Meunier, *A study of magnetically rotating arc stability using fluctuations in voltage, velocity and emission line intensitiy*, J. Phys. D:Appl. Phys., 28, 2505-2513, 1995.
14. **G. Kim**, J.-L. Meunier, F. Ajersch, *Experimental study of the effect of nitrogen on titanium-arc cathode erosion*", IEEE Trans. Plasma Sci., Vol. 23, No. 6, pp. 1001-1005, Dec. 1995.
13. **N. Desaulniers-Soucy**, J.-L. Meunier, *Temperature and Density Profiles of Magnetically Rotating Arcs Burning in Contaminated Argon*, Pl. Chem. and Pl. Proc., Vol. 15, No. 4, pp. 629-651, 1995.
12. **M. Kandah,** J.-L. Meunier, *Study of Microdroplets Generation from Vacuum Arcs on Graphite Cathodes*, J. Vac. Sci. Technol. A, 13(5), pp. 2444-2450 , Sept/Oct. 1995.
11. J.-L. Meunier, **N. Desaulniers-Soucy**, *Erosion Rate Evaluation of Plasma Torch Electrodes from Measurements of the Emitted Metal Vapour Radiation*, J. Phys. D: Appl. Phys., 27, pp. 2522-2525, 1994.

10. J.-L. Meunier, **M. Douyon de Azevedo**, *Carbon cathode spot plasma flux distributions in low pressures of nitrogen: some evidences for the $C^+ + H_2 \rightarrow CH^+ + H$ reaction*, IEEE Trans. on Plasma Science, Vol. 20, No. 6, pp. 1053-1059, Dec. 1992.
9. J.-L. Meunier, S. Vacquié, R.J. Munz, *Spectroscopic Study of a Magnetically Rotating Arc Between Copper Electrodes in Contaminated Argon*, Plasma Chemistry and Plasma Processing, Vol. 12, No. 1, pp. 1-16, 1992.
8. **M. Douyon de Azevedo**, J.-L. Meunier, *Vacuum Arc Deposition of Carbon Thin Films in a Low Pressure of Hydrogen*, IEEE Trans. on Plasma Science, Vol. 19,, No. 5, pp. 734-739, Oct. 1991.
7. J.-L. Meunier, *Pressure Limits for the Vacuum Arc Deposition Technique*, IEEE Trans. on Plasma Science, Vol. 18, No. 6, pp. 904-910, Dec. 1990.
6. **M. Douyon de Azevedo**, J.-L. Meunier, *Ionic Flux Distributions for the Vacuum Arc Deposition of Diamondlike Films*, Chemical Engineering Science, Vol. 45, No. 8, pp. 2475-81, 1990.
5. J.-L. Meunier, M.G. Drouet, *Experimental Study of the Effect of the Gas Pressure on Arc Cathode Erosion and Redeposition in He, Ar and SF6 from Vacuum to Atmospheric Pressure*, IEEE Trans on Plasma Science, Vol. PS-15, No. 5, pp. 515-19, Oct. 1987.
4. M.G. Drouet, Ph. Poissard, J.-L. Meunier, *Measurements of the Current Distribution at the Anode in a Low Current Vacuum Arc*, IEEE Trans. on Plasma Science, Vol. PS-15, No. 5, pp.506-9, Oct. 1987.
3. M.G. Drouet, J.-L. Meunier, Ph. Poissard, P. Kieffer, *Measurement of the Current Distribution at the Anode of an Arc Burning in a Gas and in Vacuum*, J. Phys. E: Sci. Instr., No. 20, pp. 625-6, 1987.
2. M.G. Drouet, J.-L. Meunier, *Influence of the Background Gas Pressure on the Expansion of the Arc-Cathode Plasma*, IEEE Trans. on Plasma Science, Vol. PS-13, No. 5, pp. 285-7, Oct. 1985.
1. J.-L. Meunier, M.G. Drouet, *Bouncing Expansion of the Arc-Cathode Plasma in Vacuum Along the Transverse Applied B Field*, IEEE Trans. on Plasma Science, Vol. 11, No. 3, pp. 165-168, Sept. 1983.

2.2 Conference Contributions : (2003-present) (* = refereed with proceedings)

102.* **Pristavita R.**, Meunier J.-L. and Berk D., *Extraction and identification of volatile compounds from carbon black produced by thermal plasma,* 8th World Congress in Chemical Engineering, Montreal (Canada), Aug 23-27 2009.

101.* Tavares J., Coulombe S. and Meunier J.-L., *Dual plasma synthesis of single-crystal titanium nitride nanoparticles*, ICPIG-29, Cancun (Mexico), July 12-17 2009.

100.* **Baddour C.**, Meunier J.-L, *Carbon nanotube synthesis on stainless steel 304 by thermal CVD without the addition of an external catalyst: surface characterization,* Carbon'09, Biarritz (France), June 2009.

99.* **(Best paper award) Dionne M.**, Coulombe S., Meunier J.-L., *Plasma-Enhanced Electron Emission from Carbon Nanotube Array Cathodes*, Paper 1.1.9, 19th Intl. Symp. on Plasma Chemistry, Bochum, Germany, July 2009.

98.* **Pristavita R.**, Meunier J.-L., Berk D., *The Synthesis and Functionalization of Nanostructured Carbon Black by Thermal Plasma for Use in PEM Fuel Cells*, Paper P3.16.1, 19th Intl. Symp. on Plasma Chemistry, Bochum, Germany, July 2009.

97.* **Mendoza Gonzalez N.**, Lakshminarayana R., Carabin P., Meunier J.-L., *A Three Dimensional Model of a DC Plasma Torch Used in Waste Treatment Applications*, Paper 2.2.24, 19th Intl. Symp. on Plasma Chemistry, Bochum, Germany, July 2009.

96.* **Azem. A**, Meunier J.-L., *Nitrogen Doped Diamond TP-CVD Deposition by a RF-Inductively Coupled Plasma*, Paper 3.7.1, 19th Intl. Symp. on Plasma Chemistry, Bochum, *Germany*, July 2009.

95.* **Vandsburger L.**, Tavares J., Coulombe S., and Meunier J.-L., *Surface modification of multi-walled carbon nanotubes for enhanced dispersion and stability using a RF glow discharge*, 19th Intl. Symp. on Plasma Chemistry, Bochum, Germany, July 2009.

94. **Vandsburger L.**, Coulombe S., Meunier J.-L., *Chemical surface modification of carbon nanotubes for preparation of aqueous nanofluids*, Colloque Plasma-Québec, Montréal, May 2009.

93. **Dionne M.**, Meunier J.-L., Coulombe S., *Prédiction pour l'émission électronique stimulée par plasma pour des réseaux de nanotubes de carbone*, Colloque Plasma-Québec, Montréal, May 2009.

92. Tavares J., Coulombe S., Meunier J.-L., *Dual plasma synthesis of sincle-crystal cubic titanium nitride nanoparticles*, Colloque Plasma-Québec, Montréal, May 2009.

91. **Mendoza-Gonzalez N.Y.**, Rao L., Carabin P., Kaldas A., Meunier J.-L., *Modélisation numérique 3-D de torches à plasma DC à haute enthalpie afin d'optimiser le design d'électrodes*, Colloque Plasma-Québec, Montréal, May 2009.

90. **Mendoza-Gonzalez N.Y.**, Pristavita R., Meunier J.-L., Berk D., *Synthèse de noir de carbone fonctionalisé par plasma thermique ICP: Optimisation numérique*, Colloque Plasma-Québec, Montréal, May 2009.

89. **Vandsburger L.**, Coulombe S. et Meunier J. -L., "*Projet d'incorporation de nanotubes de carbone dans un nanofluide: Problématique et méthodologie*," Plasma-Québec meeting, 22-23 mai 2008

88. **Pristavita R.**, Meunier J.-L., Berk D., *Synthèse et fonctionalisation de noir de carbone nanostructuré par plasma thermique pour les piles à combustible PEM*, Plasma-Québec meeting, 22-23 mai 2008.

87.* **Dionne M.**, Coulombe S. and Meunier J. -L., *Energy exchange during electron emission from carbon nanotubes: from the tip cooling effect to the destruction of the emitter, COMSOL Conference*, Boston (USA), October 9-11 2008.

86. **Dionne M.**, Meunier J. -L. and Coulombe S., *Enhancing electron emission from surfaces: carbon nanotube arrays on commercial grade anodized aluminum*, Functional Coatings and Surface Engineering Symposium, Montréal (QC), June 1-4 2008.

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84. **Guo L.**, Meunier J.-L., *Modélisation d'une torche à plasma DC en expansion supersonique pour la production de nanotubes de carbone*, Plasma-Québec meeting, 22-23 mai 2008.

83. **Baddour C.**, Meunier J.-L., *Vers une émission électronique 3-D pour des électrodes à fort courant : feutre nanométrique à base de TiN et de nanotubes de carbone*, Plasma-Québec meeting, 22-23 mai 2008.

82.* **Baddour C.**, J.-L. Meunier, *Carbon nanotube synthesis on stainless-steel for use in a nanotube-titanium nitride nanocomposite*, IEEE 8th International Conference on Nanotechnology, paper 549920, Arlington, TX, Aug. 18-21 2008

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80.* **M. Dionne**, J.-L. Meunier, S. Coulombe, *Electrostatic screening effects between vertically aligned carbon nanotubes and fast transient joule heating during field emission*, COMSOL Conference, Oct. 2007.

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78.* **G.-P. Dai**, J.-L. Meunier, *Large-scale continuous synthesis of high purity carbon nanotubes in a dc thermal plasma torch reactor,* Proc. 18th Int. Symp. on Plasma Chemistry, Kyoto (Japan), Aug. 2007.

77.* **L. Guo**, J.-L. Meunier, I.D. Hinkov, *The evolution of carbon precursors for carbon nanotube synthesis in a DC plasma torch reactor,* Proc. 18th Int. Symp. on Plasma Chemistry, Kyoto (Japan), Aug. 2007.

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75. J.-L. Meunier (**Invited Paper**), **D. Harbec, L. Guo**, *Thermal Plasma Synthesis : Processes Involving Both the Catalyst Precursor Generation and the Nano-structures Growth on this Catalyst*, Intl Round Table on Thermal Plasma Technology, Sharm El Sheik, Jan 2007 .
74.* **NK. Reddy**, L. Rao, C. Qin, S. Coulombe, J.-L. Meunier, R.J. Munz, *Carbon nanotubes as filters for nanoparticles*, 56th Canadian Chemical Engineering Conf., U. de Sherbrooke, Oct. 15-18, 2006.
73. **N.K. Reddy**, J.-L. Meunier, S. Coulombe, *Growth of carbon nanotubes on various substrates by thermal CVD*, 18th Canadian Materials Science Conf., McGill U., June 19-21 2006.
72. **A. Azem**, J.-L. Meunier, S. Omanovic, *Synthèse et étude de films de diamant dopés à l'azote et au bore*, 74e Congrès de l'ACFAS – Colloque : Science et ingénierie des plasmas, U. McGill, 18-19 mai 2006.
71. **C. Baddour**, J.-L. Meunier, *Projet d'un dépôt nano-composite de carbone adamantin contenant des nanotubes de carbone*, 74e Congrès de l'ACFAS – Colloque : Science et ingénierie des plasmas, U. McGill, 2006.
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69. **M. Dionne**, S. Coulombe, J.-L. Meunier, *Le mouvement de la tache cathodique d'un arc électrique sur une cathode froide*, 74e Congrès de l'ACFAS – Colloque : Sci. & ing. des plasmas, U. McGill, 2006.
68. **D. Harbec, L. Guo**, J.-L. Meunier, *Produire des Nanotubes de Carbon (NTC) par la Technologie des torches à Plasma DC*, 74e Congrès de l'ACFAS – Colloque : Science et ingénierie des plasmas, U. McGill, 2006.
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2.3 Invited talks:

12. J.-L. Meunier (Invited Paper), D. Harbec, L. Guo, *Thermal Plasma Synthesis : Processes Involving Both the Catalyst Precursor Generation and the Nano-structures Growth on this Catalyst*, Intl Round Table on Thermal Plasma Technology, Sharm El Sheik, Jan 2007 .
11. J.-L. Meunier, invited paper, joint CAP Congress/Photonics North Congress, Québec, June 3 2002 (Ref. 56 in Conference section 2.2 above)
10. J.-L. Meunier, invited lecture, Club EDF-Arcs Électrique Meeting, Paris, France, March 15, 2000 (Ref. 47 in Conference section 2.2 above).
9. J.-L. Meunier, Conférencier invité, *Intéraction arc-cathode froide*, INSA (Institut National de Sciences Appliquées), Toulouse, France, 5 avril 2000.
8. J.-L. Meunier, Conférencier invité, *Intéraction arc-électrode*, LAEPT, Université Blaise Pascal, Clermont-Ferrand, France, 13 avril 2000.
7. J.-M. Meunier, invited lecture, *Arc-Cold Cathode Interaction*, Chemical Engineering Department, A&M University, College Station, Texas, USA, May 10 2000.
6. J.-L. Meunier, conférencier invité, *Intraction plasma d'arc électrique - cathode froide: Propriétés et importance d'une pression locale élevée au voisinage du spot*, INRS-Énergie et Matériaux, Varennes, Qc, Canada, 16 juin 2000.
5. J.-L. Meunier, invited talk, *Cold cathode arc attachment: the importance of the high local pressure*, 13th Int. Symp. on Plasma Chem.(ISPC-13), Beijing, China, Aug.1997 (ref. 36 in section 2.2 above).
4. J.-L. Meunier, invited talk, *Fullerene studies from cathodic arc carbon plasma expansion in helium*, Department of Chemistry, Warsaw University, Poland, 1994.
3. J.-L. Meunier, invited lecture, *Cathode spot phenomena*, Laboratoire de décharges dans les gaz, CPAT, Université Paul Sabatier, Toulouse, France, 1994.

2.4 Patents

4. **C. Baddour** and J.-L. Meunier, *Simple method for the production of carbon nanotube composites and the novel nanocomposites produced thereof*, US PTO application No. 61183620, June 3 2009.
3. **M. Dionne**, S. Coulombe and J.-L. Meunier, *Anodic aluminum oxide templates with 2-D linear ordering on commercial grade aluminum*, US PTO application, May 2009.
2. **D. Harbec** and J.-L. Meunier, *Method for producing carbon nanotubes using a thermal plasma torch,* Publication number: 2004046030/WO-A1; date: June 3, 2004.

1. J.-L. Meunier and **M. Kandah**, *Particle-free cathodic arc carbon ion source*, US patent Number: US 6,261,421 B1; July 17 2001.

3. Other Evidence of Impact and Contributions

1. Paper [99](Germany, 2009) in section 2.2 received the "best paper award" in this international conference. ISPC (Intl. Symp. on Plasma Chemistry) has historically been the most important conference in our field, and this award was attributed, on top of the quality of the paper, to the significance of the work enabling new plasma devices with optimal surface emission processes, i.e. to our "new family of electrodes".
2. The conference paper [75] (Sect. 2.2) was on invitation only, and was aimed at grouping world leaders in the thermal plasma community in order to assess the state of the technology and try to assess needs and orientations we should target in the years to come. My invitation to give a talk related to the new innovative trend we developed by being able to first nucleate homogeneously nano-scale templates in the thermal plasma stream, and on this template grow heterogeneously the nanoscale product of interest (CNT in our case) downstream of the same plasma stream. This concept was entirely new.
3. The talk given by Baddour in Biaritz (Sect. 2.2 ref [100]) followed our paper in the journal Carbon (Sect 2.1 ref [49]). This paper attracted attendees from the other 3 parallel sessions and literally crowded the conference room for the duration of the talk, indicating the large interest generated by the new developments.

5. Contributions to the training of HQP

The HQP list in Part I of this NSERC CV covers the years 2003-2009. A total of over 30 graduate students have been formed since the late 1980s.

The number of graduate students generally goes with the funding, the interest of UG students however is a good sign of the passion one team may develop, particularly when these UG students follow to M.Eng. degrees within the team. A total of 16 UG students were formed in the last 6 years, and 3 (possibly 4) have or are intending to continue towards a M.Eng.(Thesis). I tend to give USRA projects with formation on state of the art technologies and research topics in line with our current needs of understanding and applications, i.e. publishable results.